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## **RIDE SEVERITY INDEX – A NEW APPROACH TO COMPARING WAVE SLAM ACCELERATION RESPONSES OF HIGH-SPEED CRAFT**

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### **Administrative Information**

The work described in this report was performed by the Combatant Craft Division (Code 23) of the Ship Systems Integration and Design Department at the Naval Surface Warfare Center, Carderock Division (NSWCCD). The objectives of the overall task were to develop data analysis guidelines, to seek alternative analysis techniques, and to develop comparative analysis tools for design evaluation. This effort was sponsored by the Office of Naval Research, Sea Warfare Applications Division (Code 333), Arlington, VA, and funded under document numbers N0001408WX20581 and N001408WX20619.

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## Summary

This paper presents a simplified approach to quantifying the comparison of acceleration responses of high-speed in rough seas. Statistical acceleration values, used to characterize craft seakeeping responses, including average of the highest 1/3<sup>rd</sup>, 1/10<sup>th</sup>, and 1/100<sup>th</sup> peak accelerations and the root-mean-square (RMS) acceleration, are used to define the relative Ride Severity Index (RSI). The paper first summarizes an unambiguous computational procedure for multiple investigators to calculate similar acceleration values. It then explains the theory and rational for relating statistical acceleration ratios to an indication of potential damage, whether due to cumulative wave impacts or single severe slam events, that can be used in comparative assessments of structural integrity, equipment susceptibility to malfunction, or personnel comfort and safety. Example comparison plots and computed values of RSI are presented to illustrate the simplicity of the approach, and to demonstrate the ability to quantify what heretofore has relied primarily upon the subjective experience of operators.

## Introduction

### Craft Seakeeping Trials

The Combatant Craft Division (CCD) of Naval Sea Systems Command (NAVSEA), Naval Surface Warfare Center Carderock Division conducts at-sea performance trials of craft such as the one shown in Figure 1 for numerous government agencies and private industry (both manned and unmanned new technology prototypes and new acquisition craft).



Figure 1. High-Speed Craft Trial

During these trials accelerometers are typically installed to capture the dynamic motions of the craft in waves. These motions are of interest because they are applied in craft design and comparative craft evaluations to address multiple factors associated with seakeeping, including hull design loads, stability, component ruggedness, and crew or passenger comfort and safety.

## Root Mean Square Beginnings

In general terms, the ride severity of any vehicle often includes a discussion of the effect of vehicle motions on passengers. This was especially true in the airline and automobile industries where noise, temperature, and vibrations in vertical and lateral directions are related to passenger comfort. The vibration amplitudes are typically characterized by root mean square (RMS) acceleration values. It is no surprise that technical advances documented in early ride quality symposia (reference 1) greatly influenced marine vehicle researchers who applied statistical measures and used RMS acceleration criteria to compare the motions experienced on displacement hulls, surface effect ships, and hydrofoils with established criteria for motion sickness and fatigue (reference 2).

## Need for Change

In the mid-1970's it was reported that when marine vehicle motions include shocks or impulsive velocity change, then RMS acceleration values have no relation to crew comfort or the potential for injury for crest factors (peak acceleration to RMS ratio) greater than three (reference 3). It was also reported that there was a general dissatisfaction with the lack of valid hard data upon which meaningful comparisons between different craft could be based, and there was no fully satisfactory criterion for judging the ride quality of high-speed craft in rough seas (reference 4). While many testimonials and subjective evaluations of ride quality could be provided by operators and passengers, there was no process for acquiring or processing recorded acceleration data for quantitative comparisons (reference 5). It was even reported that the valid comparison of the ride quality of different high-speed craft could only be achieved by side-by-side trials using essentially duplicate instrumentation systems (reference 4).

## Objective

The objective of this report is to present a new approach to quantifying comparisons of acceleration responses of high-speed craft that are operating in conditions where the potential for damage to equipment or structure, or crew discomfort or fatigue due to wave slams are of higher interest than slower and lower amplitude craft motions typically associated with motion sickness. Acceleration values used to characterize craft seakeeping responses, including average of the highest  $1/3^{\text{rd}}$ ,  $1/10^{\text{th}}$ , and  $1/100^{\text{th}}$  peak accelerations and root-mean-square (RMS) accelerations are coupled with simplifying assumptions related to wave damage potential to derive the Ride Severity Index. When coupled with Navy crew comfort and performance effectiveness criteria (i.e.,  $A\ 1/10 = 1.0g$ ,  $1.5g$ , and  $3.0g$ ), the RSI can be used to evaluate ride quality.

## Peak Accelerations

### Rigid Body Acceleration

Peak rigid body acceleration values recorded during tests of high-speed craft in both model-scale and full-scale have served as key parameters for hull structure design and seakeeping comparisons (references 6 to 10). Figure 2 shows a plot of a typical vertical acceleration time history recorded on a 36 foot craft at the longitudinal center of gravity while

operating in seas greater than 3.2 feet (significant wave height) at an average speed greater than 20 knots. A 240-second plot is shown for illustrative purposes.

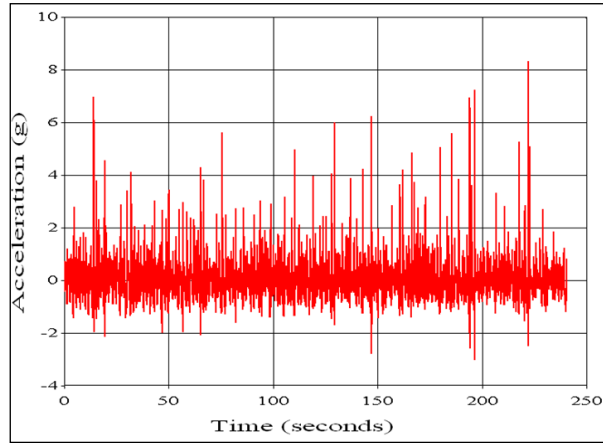


Figure 2. Typical Vertical Acceleration Plot

Typically, peak acceleration amplitudes recorded during a test sequence are tabulated, and averages are calculated using a peak-to-trough approach adopted from ocean wave measurement techniques (references 11 and 12). The approach typically requires the use of buffer values in amplitude and time axes to extract a peak acceleration value for each wave encounter in the recorded data (reference 13). In addition to the RMS acceleration, three average values have been reported in numerous test and evaluation reports. These average values are referred to as the average of the highest one-third, one-tenth, and one-hundredth peak accelerations. For example, the average of the one-tenth highest accelerations is computed using equation (1).

$$A_{1/10} = \left( \frac{1}{n/10} \right) \sum_{i=1}^{n/10} A_i \quad \text{Equation (1)}$$

$A_i$  are the individual acceleration peaks (extracted from an acceleration time history) sorted in such a way that the largest amplitude acceleration has  $i = 1$  and the lowest acceleration is  $i = n/10$  ( $n$  is the number of peak accelerations). While the equation is simple and straight forward, historical implementation of peak-to-trough algorithms has been troublesome due to user subjectivity when choosing buffer values. This typically leads to different computational results by different analysts.

### Criteria for Consistency

It was recently reported that the user subjectivity in selecting peak-to-trough buffers and calculating average of the highest  $1/N^{\text{th}}$  peak accelerations could be obviated by applying three criteria in the data analysis process (references 14 and 15). The three criteria are summarized below because they are important for implementing a ride severity parameter that can be consistently calculated (and compared) by different data analysts. The goal is to achieve

consistent  $A_{1/N}$  results within a couple of percent among different analysts rather than to achieve exact results.

The first criterion deals with selection of a consistent amplitude buffer as a starting point for counting higher peak acceleration values. The second criterion deals with using a consistent buffer on the time scale to extract peak accelerations from successive wave encounters recorded in the acceleration data. The third criterion deals with extracting rigid body content from data that typically contains high frequency peaks caused by local vibrations in craft structure in the vicinity of the acceleration gage.

### Acceleration Amplitude Criterion

Review of high-speed data for planning and semi-planing hulls indicates that the RMS value of an acceleration record correlates well with the lower amplitude values associated with forces due to buoyancy, hydrodynamic lift, drag, and gravity. This is illustrated in Figure 3 by acceleration response data for a craft operating at a semi-planing speed. The blue dotted-lines are the plus and minus RMS amplitudes of the entire record. The RMS value under these conditions serves as a rational baseline for counting higher positive peak accelerations caused by wave impacts. It is recommended that the vertical threshold in peak finding algorithms be set equal to the RMS value of the acceleration record.

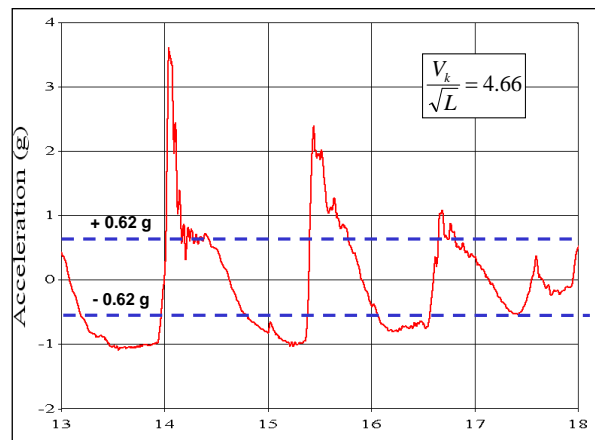


Figure 3. RMS Acceleration Baseline

### Wave Impact Period Criterion

The average time period between wave impacts can be shown to be on the order of 0.5 seconds or greater for speeds up to 60 knots and significant wave heights greater than 1.6 feet. The majority of the peak accelerations caused by wave slam events will therefore be greater than 0.5 seconds apart. It is recommended that a horizontal time value in peak finding algorithms be set equal to 0.5 seconds. This will ensure that the majority of the most significant wave slam events (i.e., highest amplitude) will be extracted by the algorithm. It is interesting to note that if the majority of significant wave encounters occurs at intervals equal to or greater than 0.5 seconds, then the wave encounter frequency is 2.0 Hz or less. Appendix A illustrates the sequence of events in a single wave encounter. A knowledge of the cause and effect

relationships between loads and craft responses for single wave slam events helps to understand statistical values such as calculated RMS and average of the highest  $1/n^{\text{th}}$  acceleration values (reference 16).

### Rigid Body Criterion

On the low end of the frequency response spectrum, the wave encounter frequency (i.e., the rigid body loading frequency or wave impacts per second) is typically less than 2.0 Hz for speeds up to 60 knots in seas characterized by significant wave heights greater than roughly 1.6 feet. Toward the higher end of the frequency response spectrum, experience has shown that large peak accelerations are caused by very small displacement flexural vibrations of structure near gages on rigid structure with frequency responses on the order of more than 20 Hz. Two typical wave slam events recorded by a vertical accelerometer in a planning craft are shown in Figure 4.

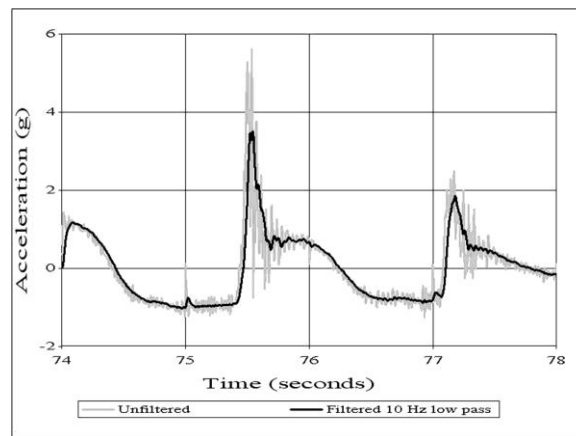


Figure 4. Estimated Rigid Body Acceleration

The grey curve is the original record without filtering. It contains high frequency oscillations on the order of 24 to 26 Hz caused by structural vibrations close to the gauge. These oscillations add significant amplitude to the acceleration response at the time of the wave slam peak acceleration response. Gauge placement should focus on structural hard spots above bulkheads, frames, or girders to minimize local flexure. The black curve was created by applying a 10 Hz low-pass Kaiser filter to estimate the vertical rigid body response (1% ripple in stop-band, 5% ripple in band-pass, stop-band frequency 20% greater than the specified band-pass frequency).

Experience in analyzing numerous sets of trials data suggests that the 10 Hz low-pass filter sufficiently removes local vibrations without severely affecting rigid body peak amplitudes. In a few cases, a 20 Hz low-pass filter was judged appropriate due to 5 to 10 Hz signals in the data. In any event, the difference in calculated  $A_{1/n}$  trends using 10 Hz and 20 Hz low-pass filters is only on the order of 11 percent to 16 percent. It is recommended that the 10 Hz low-pass filter be used as a starting point to estimate rigid body accelerations, unless further data analysis indicates use of a higher filter value. Use of filter frequency other than 10 Hz should be published with comparison results.

## Example Calculations

After the typical acceleration record shown in Figure 2 was subjected to a 10 Hz low-pass filter, one hundred fifty-one peak accelerations (this is a low sample size) were counted greater than the 0.62g RMS value. Figure 5 shows a 30-second segment with the wave slam peaks selected (triangles) and the peaks ignored (circles) by the peak-to-trough computational procedure. The largest peak in the entire record was 5.31g.

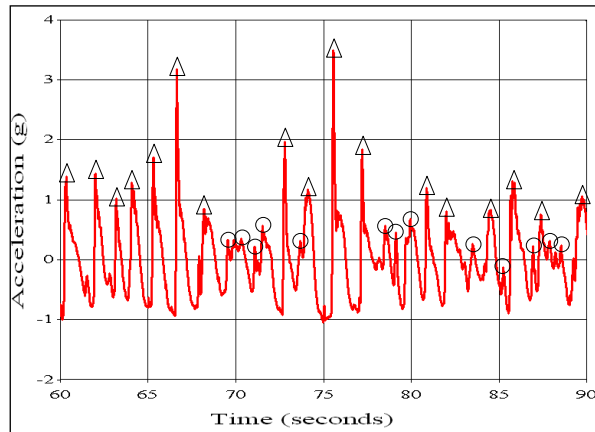


Figure 5. Peaks Selection Using Standard Criteria

Figure 6 shows all one-hundred fifty-one peak acceleration values sorted and plotted from largest to smallest (left to right). The average of the 1/3<sup>rd</sup>, 1/10<sup>th</sup>, and 1/100<sup>th</sup> highest acceleration values (2.41g, 3.48g, and 5.31g, respectively) are also shown.

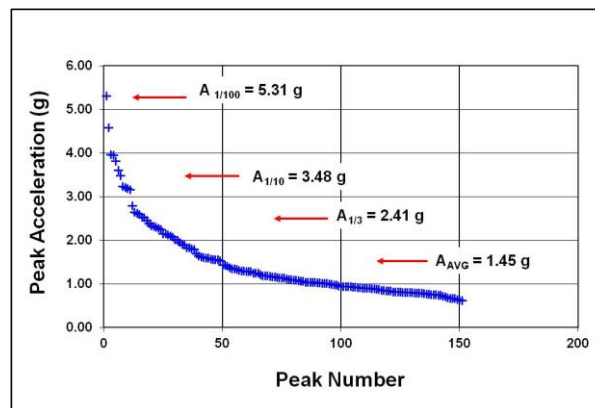


Figure 6. Sorted Peak Accelerations Greater than RMS

Figure 7 shows all one-hundred fifty-one peak accelerations plotted to show the percentage of peaks below each peak value (i.e., cumulative distribution plot). For example, the plot shows that approximately eighty percent of the peaks observed in the data have amplitudes less than 2.0g.

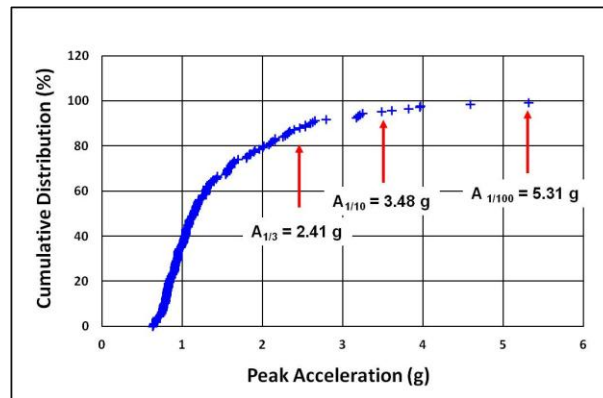


Figure 7. Peak Acceleration Cumulative Distribution Plot

### Relative Ride Severity

#### Acceleration Amplitude

In the absence of a formal definition of what is often perceived as a set of very complex parameters (parameters for six degrees of freedom could potentially be used to define ride severity), it is useful to use available vertical acceleration data in an attempt to quantify a first-order estimate of the change in the severity of a ride between conditions I and II. These conditions may be different craft, different craft speeds, different sea states, or different gauge locations on a given craft. In simple terms, a ride with lower peak accelerations associated with all wave slams and fewer wave slams at higher severities could be characterized as a better ride. Figure 8 shows two sets of peak accelerations for hypothetical conditions I and II for data sets of equal time periods.

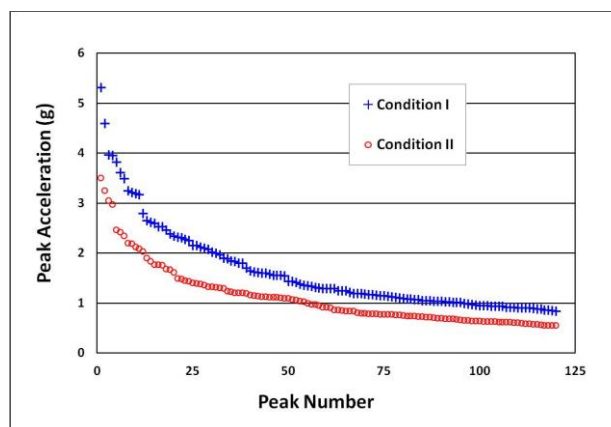


Figure 8. Example Condition I and II Peak Accelerations

The amplitudes for condition I (values from Figure 6) are clearly all greater than condition II, so the conclusion would be that condition I is a more severe ride (or more damage potential in

terms of peak accelerations). The following paragraphs explain how a ratio of wave slam peak accelerations can be used as a relative indicator of ride severity.

## **Damage Potential**

As peak accelerations due to wave slam events increase in magnitude (for constant duration shock pulses), there is a proportional increase in the potential for structural damage, or equipment malfunction (or failure), or personnel fatigue or discomfort. Unfortunately there are few simple criteria for damage other than estimates (corroborated by experience) for specifying operational limits (reference 10 and 17). In the following paragraphs the potential for wave slam damage will be discussed in terms of damage to equipment to illustrate the new approach to quantifying ride severity.

Damage mechanisms of equipment items may include failures of attachments, enclosures, and internal structures due to material over-stresses or cyclic loads, or electrical failures due to disconnects of sub-components such as plugs, sockets, or circuit cards. Material over-stresses or disconnects could occur due to a one-time severe wave slam event (maximum peak acceleration), or equipment malfunction or failure (due to disconnects) could be caused by repetitive impacts at lower amplitudes (lower peak accelerations) over a relatively long period of time. For example, in Figure 6 one of the large amplitude wave slam events could result in damage during a single slam event. The average of the highest 1/10<sup>th</sup> (3.48g) and the 1/100<sup>th</sup> (5.31g) peak accelerations are values that characterize the larger wave slam amplitudes.

Likewise, Figure 7 shows that there are many more low amplitude wave slams (80 percent) with peak accelerations less than 2.0g. Even though this amplitude may not result in damage during a single slam event, the repetition over time of many impacts could cause disconnects of sub-components such as plugs, sockets, or circuit cards. Over very long periods of time the low amplitude wave slams could also cause problems related to material or personnel fatigue.

There are innumerable ways that components can fail during a wave slam (shock) event, and there is a very broad range of different types of equipment items produced by national and international manufacturers. It is therefore not practical to define specific shock amplitudes at which damage of any type will occur. To define such levels would be a very expensive undertaking that would require repeated testing of many expensive components. There is insufficient fragility data to quantify levels above which different types of failure modes begin to occur. In the absence of fragility data, the ratio of a shock severity parameter may be used as a relative indicator of damage potential.

## **Peak Acceleration Ratio**

Experience gained from shock machine testing demonstrates that of the three basic parameters used to define the shock environment (displacement, velocity, acceleration), velocity (specifically, change in velocity) is the parameter of greatest interest when evaluating the potential for damage (references 3 and 18). These findings do not preclude the use of the peak acceleration parameter as a measure of damage potential, especially for impact events with the same or similar duration times. Reviews of many sets of high-speed craft wave slam data (craft less than approximately 52 feet long) indicate the impact periods (i.e., shock pulse periods) are on the order of 0.1 to 0.4 seconds depending upon craft displacement, average speed, and wave height. Within this relatively narrow range of impact durations an average acceleration value (average acceleration during the impact event) would also be an appropriate parameter for first

order quantification of the damage potential among many different wave slam events. A further simplifying assumption for the present comparative approach is that the peak acceleration due to a wave slam varies proportionately with the average acceleration during the same impact event. A ratio of peak accelerations for two different wave slam events can therefore be approximated by equation (2).

$$\frac{A_{RBII}}{A_{RBI}} = \frac{\Delta V_{RBII} / \Delta t_{RBII}}{\Delta V_{RBI} / \Delta t_{RBI}} \quad \text{Equation (2)}$$

The subscript RB denotes rigid body motion, delta-V is the change in velocity, and delta-t is the shock pulse duration time. For impact events with duration times of the same or similar order of magnitude, the peak vertical acceleration ratio (of each wave slam event) is proportional to the ratio of velocity change. It follows then that the ratio of peak vertical accelerations for conditions I and II is a measure of the change in damage potential between conditions I and II, and can therefore be used as a measure of relative ride severity.

Figure 9 presents the same data points shown in Figure 8 in a different format. In this plot all peak accelerations (largest to smallest) recorded during condition I are compared with the corresponding (largest to smallest) peak acceleration recorded during condition II. In other words, the largest peak for each condition is plotted together, then each of the 2<sup>nd</sup> largest peaks is plotted together, then each of the 3<sup>rd</sup> largest peaks is plotted together, and so on until all pairs of peak accelerations are plotted. Data comparison points that fall on the dotted line (slope of one) have equal acceleration values and therefore have the same damage potential and the same ride severity. Values below the dotted line indicates a better ride severity compared to condition I. Points above the dotted line indicate a worse ride severity.

The solid line with a slope of 0.68 is a linear least square fit of the data with the intercept set equal to zero. The slope is the approximate ratio of all acceleration values for condition II divided by all acceleration values for condition I, and can therefore be used as a relative indicator of the change in ride severity (i.e., damage potential).

### Ride Severity Index

The Ride Severity Index (RSI) for condition II relative to condition I is defined as the slope of the least squares fit line (with zero intercept) of a plot of  $A_{I/N}$  and RMS statistics for one condition plotted against  $A_{I/N}$  and RMS statistics for another condition. Two conditions have equal ride severity when  $RSI = 1.0$ . Values great than 1.0 correspond to a more severe ride, and values less than 1.0 are less severe. In Figure 9 the Ride Severity Index of condition II relative to condition I is 0.68. In percentage terms, the condition II ride severity is 32 percent less than condition I.

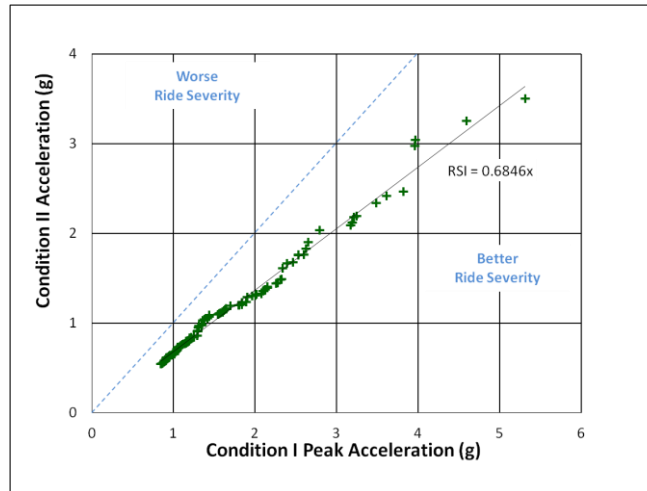


Figure 9. Ride Severity Index (RSI) Comparison Plot

### Use of $A_{1/N}$ Values

In situations where tabulations of all peak accelerations (largest to smallest) or acceleration time-history data for a craft are not available, the computed RMS,  $A_{1/3}$ ,  $A_{1/10}$ , and  $A_{1/100}$  values may be used to compute the ride severity index. As an example,  $A_{1/n}$  and RMS values for the two data sets shown in Figure 8 are listed in Table 1.

Table 1. Ride Severity Index Using  $A_{1/N}$ 

Parameter	Condition I	Condition II	Ride Severity Index
$A_{1/100}$	5.31 g	3.50 g	0.66
$A_{1/10}$	3.48 g	2.82 g	0.81
$A_{1/3}$	2.41 g	1.87 g	0.77
RMS	0.62g	0.54g	0.87
Slope	na	na	0.71

The ride severity index listed in each row is the ratio of the for corresponding pairs of  $A_{1/N}$  or RMS values in each row. The tabulated condition I and condition II accelerations are plotted in Figure 10 to illustrate the comparison. The highest point in the figure is the  $A_{1/100}$  values for conditions I and II (x-y pair), the next highest point is the  $A_{1/10}$  values for conditions I and II, and so on. In this example the least squares data fit has a slope of 0.71, so the Ride Severity Index is 0.71. This is the weighted average of the individual RSI values computed using the

ratios of  $A_{1/n}$  and RMS values. The potential for damage due to the more severe slam events is 0.65 for  $A_{1/100}$  (35 percent less than condition I) and 0.81 for  $A_{1/10}$ . The damage potential for the more frequent and repetitive lower amplitude slams ( $A_{1/3}$ ) has an RSI value of 0.77 (23 percent lower severity or reduction in damage potential).

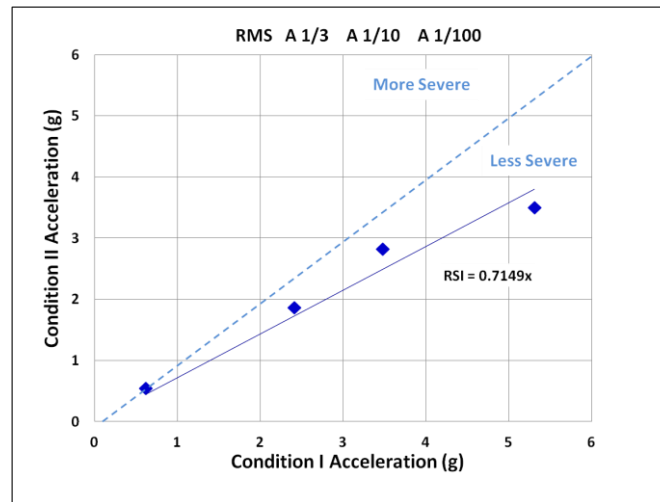


Figure 10. Average 1/Nth Acceleration RSI Plot

### Gage Location Comparisons

The RSI comparison approach can also be used to compare acceleration responses at different locations on a craft. For example, Figure 11 shows RMS,  $A_{1/3}$ ,  $A_{1/10}$ , and  $A_{1/100}$  values for vertical accelerations recorded at bow, helm, and stern locations compared to accelerations recorded at the longitudinal center of gravity (LCG). The comparison indicates the bow ride severity is approximately 2.2 times more severe than the LCG, and the stern and helm location ride severities are 3% more than and 7% less than the LCG location.

### Craft Heading Comparisons

The ride severity comparison approach can also be used to compare acceleration responses for different headings of a craft in a seaway. Figure 12 shows RMS,  $A_{1/3}$ ,  $A_{1/10}$ , and  $A_{1/100}$  values for vertical accelerations recorded at the LCG for different headings compared to a head sea course. Average speeds varied slightly from one test run to the next. The ride severity for port bow seas is approximately 4 percent less than head seas, while stern and port quarter seas are approximately 63 percent less.

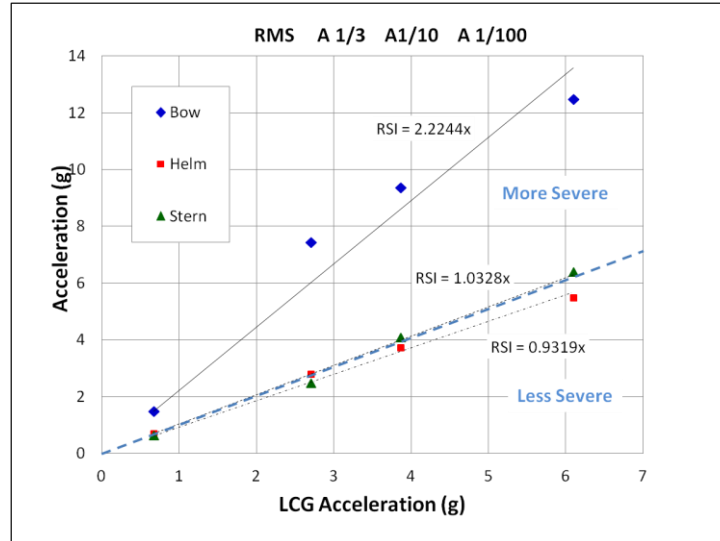


Figure 11. Gage Location Ride Severity Comparison

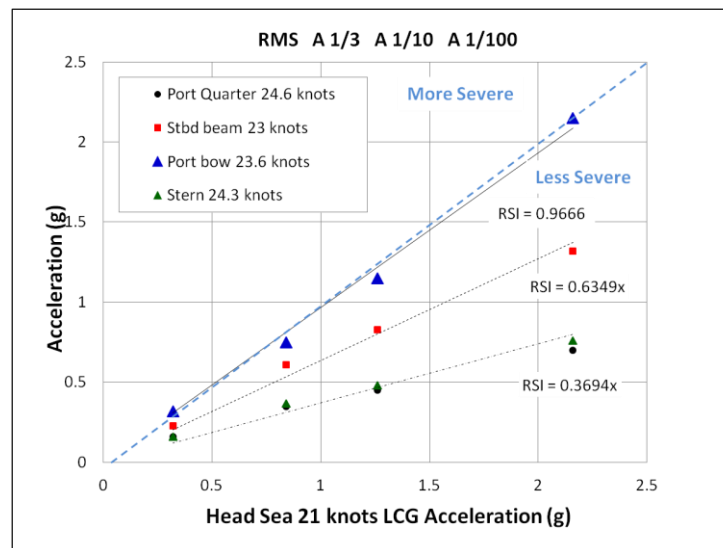


Figure 12. Craft Heading Ride Severity Comparison

### Ride Control Comparison

Figure 13 illustrates the comparison of acceleration statistics for a craft with a ride control system and without the ride control system at two different speeds. The green square data points were recorded at a nominal speed  $A$ , and the red triangle data points were recorded at a higher speed  $A + x$ . The interesting result is that the ride control system reduces the acceleration peaks by a greater amount at lower speeds (i.e., fifty-six percent reduction). At the higher speed ( $A + x$ ), the ride severity with the control system is still better than without the ride control system, but the RSI is lower. The RSI is 0.65, meaning the accelerations with the ride control are approximately thirty-five percent less than the accelerations without ride control at speed  $A + x$ .

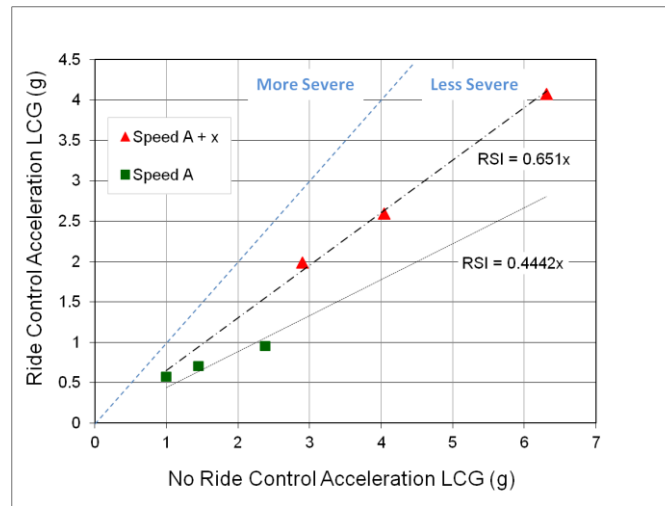


Figure 13. Ride Control System Comparison

## Ride Quality

Several key parameters can be used to describe what is typically perceived as unpleasant or uncomfortable experiences (i.e., rides) in planing craft. Fore-aft rigid body decelerations can cause individuals to lurch forwards much like the hard application of brakes in an automobile, and pitch, pitch rate, roll, and roll rate can lead to uncomfortable motions similar to whiplash, especially in the neck and spine regions. Motions in a transverse (e.g., port-starboard) direction must also be considered because of the different direction of deceleration forces (e.g., beam quartering seas) when impacting a wave. The most common parameter used to describe ride severity in a human context has been the vertical rigid body acceleration of the craft. As severity increases with speed and/or wave height, the discomfort experienced can rapidly lead to extreme discomfort or injury for seated personnel (reference 3). All of these distinguishing attributes of a ride experience determine the overall quality or roughness of the ride. When impact accelerations and rates of rotation are low, the comfort level will typically be higher (neglecting motion sickness) and the crew will be able to perform their functions without decreased proficiency over time. Good human performance attributes such as these are part of the overall description of a hull design that has good seakeeping qualities (reference 8).

Simple criteria for quantifying human performance and endurance in a wave slam environment were originally developed for naval crews (reference 10). It was reported that the severity of vertical accelerations over a period of time in a planing craft characterized by  $A_{1/10}$  less than 1.0g corresponded to an environment where a crew could effectively perform their functions for 4 or more hours. It could be construed that the comfort level in this environment was sufficiently good to allow the crew to perform their duties effectively (presumably while operating at a constant speed in the same sea state). A value of  $A_{1/10}$  equal to 1.5g corresponded to a crew being able to perform effectively for 1 to 2 hours exposure, and a value of 3.0g would lead to extreme discomfort. The three values are shown in Table 2 with four severity level ranges. The severity levels are ranges of  $A_{1/10}$  values that provide a useful baseline for comparison purposes. The arbitrary shades of color are presented to illustrate how seakeeping

data and acceleration severity levels can be conveyed in a useful data plotting format for personnel on high-performance craft in rough sea conditions.

Table 2. Severity Levels

Severity level	A <sub>1/10</sub> (g)	A <sub>1/10</sub> Range (g)	Condition
IV	3	3g - 4g	Extreme Discomfort
III	na	2g - 3g	Discomfort and limited performance
II	1.5	1g - 2g	Effective performance for 1 - 2 hours
I	1	<1g	Effective performance for 4 or more hours

The 1.0g, 1.5g, and 3.0g criteria should not be interpreted as fixed values that apply equally to all individuals, nor are they exact acceleration numbers that correspond precisely with specific comfort levels. People are extremely variable, and the tolerance of one person may vary (reference 3). For example, hypothetically, one individual may experience 1 to 2 hour limited performance after being exposed to A<sub>1/10</sub> equal to 1.5g while another individual may experience the same effects at 1.8g. The three values are, however, very useful for defining notional zones of operation where typical changes in human comfort and endurance may occur.

The values of 1g and 3g are selected as start and end conditions for defining the four severity levels shown in Table 2. 1.0g is the approximate level below which human comfort and endurance is sufficient to allow 4 or more hours of operation, and 3g is a level above which discomfort from wave impacts is judged to be extreme. Ranges between these values were developed to describe transition zones from general levels of comfort and endurance to levels of discomfort and shorter endurance. The 4g limit for Level IV is included because it was cited in the original reference as a severity transitioning from extreme discomfort to physical injury (reference 10).

Level III is intended to represent the transition between limited endurance (i.e., 1 to 2 hours) through a region of discomfort where endurance is less than 1 to 2 hours before reaching the extreme discomfort zone. The range of Level II is +/- 0.5g on either side of the 1.5g criterion to define a transition between limited and unlimited crew performance zones.

The ranges listed in Table 2 can be used to quantify ride severity by using the ratios of A<sub>1/100</sub> to A<sub>1/10</sub> and A<sub>1/3</sub> to A<sub>1/10</sub> for a craft. These ratios can be computed using recorded acceleration data. Figure 14 shows a hypothetical example of A<sub>1/100</sub>, A<sub>1/10</sub>, and A<sub>1/3</sub> values from multiple trials of one type of craft. In this figure, each data point corresponds to data recorded by one accelerometer that was processed to compute one set of A<sub>1/100</sub>, A<sub>1/10</sub>, and A<sub>1/3</sub> values. Each A<sub>1/10</sub> value is then plotted in the figure with its corresponding A<sub>1/100</sub> and A<sub>1/3</sub> values. The slope

of the best-fit lines provide average ratios of  $A_{1/100} / A_{1/10}$  equal to 1.699 and  $A_{1/3} / A_{1/10}$  equal to 0.72 for that craft.

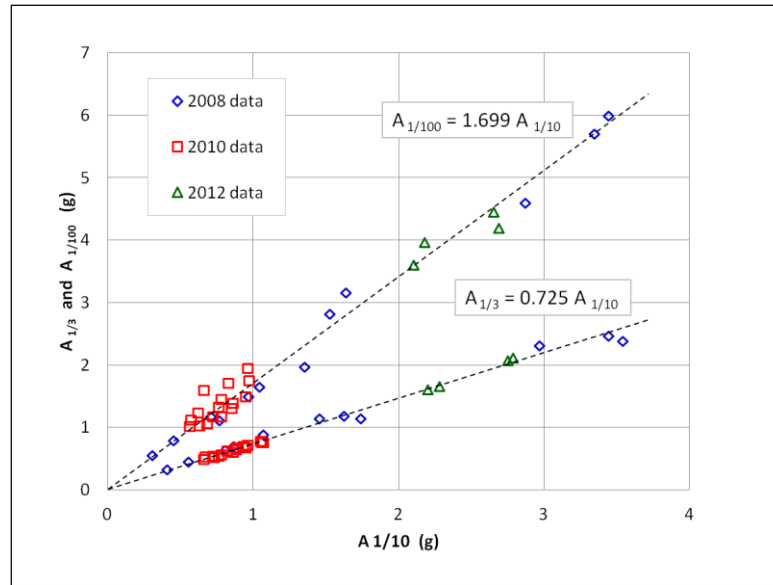


Figure 14. Average  $A_{1/N}$  Ratios from Seakeeping Data

The slope values from Figure 14 are used in Table 3 to estimate the  $A_{1/100}$  and  $A_{1/3}$  values for Levels I through IV for that craft when  $A_{1/10}$  values are 1.0g, 1.5g, and 3.0g. For example, each  $A_{1/10}$  value in the table (for Levels I through IV) is multiplied by 1.69 to estimate the corresponding  $A_{1/100}$ .  $A_{1/3}$  values are obtained by multiplying by 0.72. The last two columns on the right in Table 3 list  $A_{1/N}$  values for acceleration data recorded by gages 1 and 2 located at two different personnel stations. A comparison of numbers for the two gage locations with Level I numbers can be used to quantify the relative ride severity.

Table 3. Severity Levels and Example Data

Parameter	Acceleration (g)				Data Gage 1	Data Gage 2
	Level IV	Level III	Level II	Level I		
$A_{1/100}$	6.76	5.07	3.38	1.69	2.92	1.69
$A_{1/10}$	4.00	3.00	2.00	1.00	1.89	1.13
$A_{1/3}$	2.88	2.16	1.44	0.72	1.37	0.83

Figure 15 shows the comparison of  $A_{1/100}$ ,  $A_{1/10}$ , and  $A_{1/3}$  values for gage locations 1 and 2 (from Table 3) compared with severity Level I values. Levels II, III, and IV are also plotted as solid lines even though there are more realistically smooth transition regions.

The ride severity index (i.e., the slope of the least-squares best fit line through the data) provides a measure of the ride quality at gage locations 1 and 2 during that seakeeping trial relative to severity Level I (4 or more hours of effective crew performance). At gage 1 the ride quality is 1.78. It is 78 percent more severe than the 4 or more hour endurance Level I. At gage location 2 it is 1.04, roughly equal to the 4 or more hour Level I.

The benefit of comparing craft  $A_{1/n}$  accelerations with the 4 or more hour criterion is that the slopes of the defined severity levels are equal numerically to their  $A_{1/10}$  value. For example, the line between discomfort and extreme discomfort has a slope of 3.0. In many instances the slope of the best fit line through recorded data will be close to the  $A_{1/10}$  value, but it is typically larger or smaller depending upon the amplitudes of wave slams that were used to compute the  $A_{1/100}$  value.

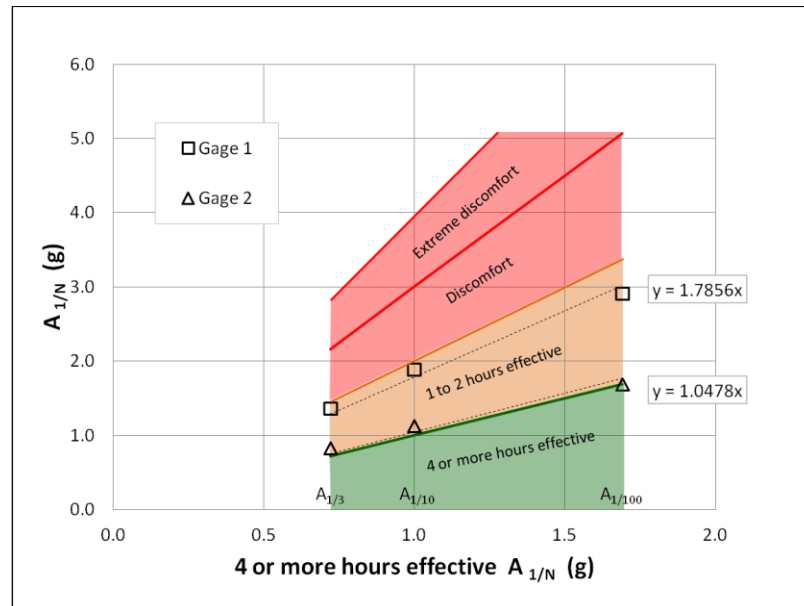


Figure 15. Relative Ride Quality Plot

## Conclusions

Calculated  $A_{1/N}$  and RMS values have been used for many decades to characterize and compare peak accelerations of craft response motions in waves. The claim that the RSI is a new approach is merely a reflection of the use of all peak accelerations above the RMS value (as in Figure 9), or the use of all four historical values of interest, including RMS,  $A_{1/3}$ ,  $A_{1/10}$ , and  $A_{1/100}$  values (as shown in Figures 10 to 13) in a single comparison measure.

In this report, the vertical rigid body acceleration is presented to illustrate the ride severity comparison approach, but its application to other rigid body parameters such as vertical velocity, pitch, roll, and surge (or their rates of change) may also be helpful.

When coupled with the generalized approach for computing rigid body  $A_{1/n}$  accelerations, the RSI is especially useful for answering the question, “how much worse (or better) was the ride severity compared to other ride conditions?” This can also be useful where the comparison baseline is quantifiable by itself, like the comfort and endurance criteria for personnel. When the 4 or more hour effective personnel criteria is selected ( $A_{1/10} = 1.0g$ ), the ride severity index can be used as a measure of the relative ride quality for a given craft condition in terms of vertical rigid body acceleration as shown in Figure 15. A more rigorous treatment of total ride quality will include surge, sway, pitch, and roll parameters. The intent here is merely to show in the interim how consistent and comparable  $A_{1/n}$  values derived from estimates of rigid body acceleration may be used to quantify ride quality using previously published criteria.

The RSI is not by itself an important result that will directly affect craft design or craft motion evaluations in the short term. Its usefulness can only be evaluated over time, where experience will determine whether or not it can be used by craft designers, evaluators, or testers to better understand the effects of wave impacts, large and small, on craft seakeeping. In the short term, it may prove useful merely by its ability to quantify a skilled operator’s perception of the ride severity of two different craft, or two different sea conditions, or in cases where a single operator cannot drive multiple craft it can quantify the subjective perceptions of several operators. Another potential use will be the ability to compare craft acceleration values recorded now with data recorded for new craft in the future (e.g., ten years from now). This will depend however upon the consistent use of a common method to calculate  $A_{1/n}$  values (see Appendix B and reference 14).

## Symbols, Abbreviations, and Acronyms

A.....	Peak Vertical Acceleration (g)
CCD .....	Combatant Craft Division
$\Delta V$ .....	Change in Craft Vertical Velocity due to wave impact
$\Delta t$ .....	Time duration of wave impact
ft .....	Feet
g.....	Acceleration Due to Gravity (32.2 ft/sec <sup>2</sup> )
Hz.....	Hertz (cycles per second)
LCG.....	Longitudinal Center Of Gravity
msec .....	Millisecond
n.....	number of peak accelerations in a data record
N, M .....	integer value of 3, 10, or 100
NAVSEA .....	Naval Sea Systems Command
RMS .....	root mean square
RSI .....	Ride Severity Index
sec .....	second

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## Appendix A. Wave Slam Sequence of Events

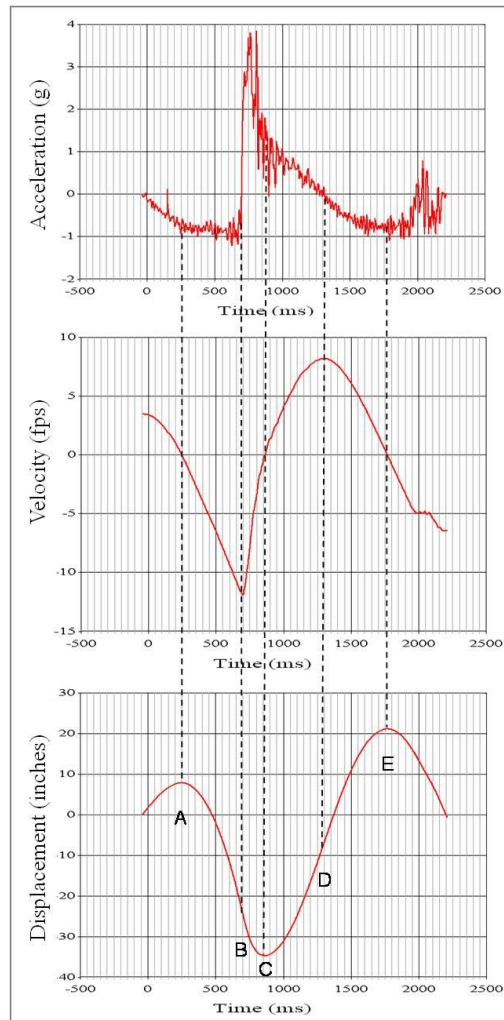


Figure A1. Typical Wave Slam Sequence of Events

Figure A1 is useful to illustrate typical motion at a craft's LCG before, during, and just after a wave slam event. The data is from a 36 foot craft. During period A to B, the craft drops from a maximum height and impacts the water with a maximum negative velocity at time B. The wave impact (slam) begins at point B. The force of the impact is seen as an almost instantaneous jump to a maximum acceleration. From time B to C the craft continues to move down in the water, the velocity approaches zero, and the acceleration decreases rapidly to an ambient value. The impact event is complete at time C. From time C to D the combined forces of buoyancy and hydrodynamic effects continue to push the craft upward, but the net force (and the acceleration) approaches zero. Between time D and E the hull below the LCG rises vertically and the velocity approaches zero.

## **Appendix B. Standardized $A_{1/N}$ Computational Approach**

The following four-step standardized approach is recommended for calculating the average of the  $1/N^{\text{th}}$  highest peak accelerations for a given acceleration time history recorded in any orientation axis (reference 14). The computational approach and the interim criteria are based on analysis practices that have evolved over a number of years at the Combatant Craft Division of Naval Surface Warfare Center, Carderock Division as a set of best-practices for achieving repeatability when computations are performed by different data analysts.

### **1. Frequency Analysis**

The first step in the data analysis process is the computation of a frequency spectrum in the 0.1 to 100 Hz range and plotting the results as illustrated in Figure 4. If the largest spectral amplitudes are less than 2 Hz, then the data can be low-pass filtered to estimate rigid body motions (remove higher frequency flexural components).

### **2. 10-Hz Low-Pass Data Filter**

As a starting point for data analysis, application of a 10-Hz low-pass filter to the acceleration record to estimate rigid body acceleration motions is recommended. Review of full-scale trials data indicates that a 10 Hz low pass filter is often appropriate to estimate the rigid body accelerations for gages positioned on stiff structure (e.g., bow, LCG, stern), where frequencies greater than 18 Hz to 20 Hz are often associated with local vibrations of structural elements in the vicinity of the gage.

In some instances a higher low pass filter may be appropriate (e.g., 20 Hz or 30 Hz) to estimate the motions at gage positions on or near shock isolated seats, masts, arches, or deck plates, just to name a few, where dominate motions may be in the 5 Hz to 15 Hz range. Published results should always include the filter type and amplitude.

### **3. RMS Calculation**

The RMS value for the 10-Hz low pass filtered acceleration record should then be calculated. Its value establishes a rational baseline for identifying higher acceleration peak amplitudes induced by wave impacts.

### **4. Calculation of $A_{1/N}$ Values**

A peak-to-trough algorithm with the following interim criteria to select peak amplitudes from the acceleration time history is recommended. The vertical threshold should be equal to the RMS acceleration for the time history, and the horizontal threshold should be equal to one-half the data sampling rate (i.e., 0.5 seconds).

The peak acceleration values are then tabulated from highest to lowest amplitudes and a cumulative percentage distribution curve can be derived. Finally, the average of the highest  $1/n^{\text{th}}$  peak values using equation (1) is calculated.

## Example Calculations

After the typical acceleration record shown in Figure 2 was subjected to a 10-Hz low-pass filter, one-hundred fifty-one peak accelerations (this is a low sample size) were counted greater than the 0.62g RMS value. Figure B1 shows a 30-second segment illustrating the wave slam peaks selected (triangles) and the peaks ignored (circles) by the peak selection procedure. The largest peak in the entire record was 5.31g. Figure 6 shows all one-hundred fifty-one peak acceleration values sorted and plotted from largest to smallest (left to right), and Figure 7 shows the cumulative distribution of all the peaks below discrete values. In each figure the average of the 1/3<sup>rd</sup>, 1/10<sup>th</sup>, and 1/100<sup>th</sup> highest acceleration values are labeled (2.41g, 3.48g, and 5.31g, respectively).

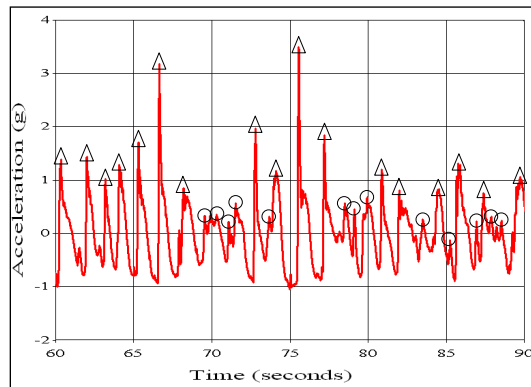


Figure B1. Peaks Selected Using Standard Criteria

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